High Clouds Microphysical Retrievals Intercomparison

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Introduction

The ARM Cloud Properties Working Group (CPWG) consists of several breakout groups that examine scientific problems related to specific cloud classifications (e.g. high clouds, low clouds, cumulus clouds etc.). The High Clouds group is involved in an intercomparison of retrieval algorithms that produce cloud radiative and microphysical properties (ice water path, optical depth, and particle size) for ice only clouds. Accurate retrieval of cloud properties is important for radiative transfer modeling and parameterization development for general circulation models, both of which are goals of the ARM program. The goal of this intercomparison is to recommend a group of algorithms with well defined uncertainties for implementation in the micro_base value added product (VAP). The goal of the micro_base VAP is to provide cloud microphysical properties for all times and heights for clouds that exist above the ARM sites. All algorithms recommended for implementation into micro_base must be published in a peer review journal.

A number of both passive and active remote sensing retrieval algorithms are currently used to estimate the microphysical properties of upper tropospheric clouds. Examples of these algorithms include spectral infrared (AERI), radar reflectivity based empirical regressions (EMP), radar reflectivity – IR radiometer (ZIR), lidar/radiometer (LIRAD), lidar – radar (LR), and radar Doppler moments (ZV) techniques. Table 1 lists each algorithm included in this study.

Table 1. Algorithms Included in Study.

Acronym	Algorithm Type	Reference
Comstock-LIRAD	Lidar-IR radiometer	Comstock and Sassen (2001)
DeSlover-AERI	Spectral Infrared (AERI)	DeSlover et al. (1999)
Donovan-LR	Lidar-Radar	Donovan and van Lammeren (2001)
Illingworth-EMP	Empirical (Z-IWC)	Liu and Illingworth (2000)
Mace-ZV	Radar Doppler Moments	Mace et al. (2002)
Mace-ZIR	Radar Reflectivity-IR	Mace et al. (1998)
Matrosov-ZV	Radar Doppler Moments	Matrosov et al. (2002)
Matrosov-ZIR	Radar Reflectivity-IR	Matrosov (1999)
Matrosov-EMP	Empirical	Matrosov et al. (2003)
Mitchell/d'Entremont-AERI	Spectral Infrared (AERI)	Mitchell and d'Entremont (2000) and Mitchell et al. 2003
Sassen-EMP	Cloud Top Temperature Empirical	Sassen et al. (2002)
Turner-AERI	Spectral Infrared (AERI)	Turner (2003)
Wang-LR	Lidar-Radar	Wang and Sassen (2003)

In this first stage of the intercomparison, we compare layer-mean ice water path (IWP), cloud particle characteristic size (D), and optical depth (τ) derived from each retrieval algorithm for 11 cases obtained at the Southern Great Plains (SGP) site and during the Surface Heat Budget of the Arctic Ocean (SHEBA) field campaign. This direct comparison of ground-based retrieval algorithms allows us to examine how well we can retrieve cloud microphysical properties and assess the strengths, weaknesses, and overall accuracy of each technique. Since the various algorithms do not use a common definition of particle effective radius, we define the characteristic particle size as $D=IWP/\tau$. Cases were chosen to cover a wide variety of high cloud sky conditions (such as thin, thick etc.). Several of the cases have coincident aircraft in situ data for comparison. Since several algorithms use similar instruments or assumptions, we group algorithms accordingly to help isolate cloud situations where each algorithm class performs well and where each fails. The radar reflectivity empirical relationships are used as a baseline for examining the retrieval based algorithms.

The valid range of optical depth for all algorithms combined is between approximately 0.01 and 10.0. Since certain algorithms perform best for thin clouds and others perform best for thick clouds. We will discuss the results according to 3 optical depth regions: very thin ($\tau<0.1$), thin ($0.1<\tau<1$), and thick ($\tau>1$). We will also discuss algorithms in terms of the instruments and assumptions, such as non-IR based algorithms (ZV, LR, EMP) and IR based algorithms (AERI, LIRAD, ZIR). The empirical relationships are used as reference for IWP and particle size, while the Raman lidar is used as reference when comparing optical depth.

Very Thin Clouds ($\tau<0.1$)

Optically thin clouds are difficult to measure for several reasons. First, algorithms that use infrared radiance measurements in the atmospheric window (ZIR, AERI, LIRAD) are limited when the cloud optical depth is below 0.1 because the infrared radiance emitted by the cloud is small compared with the background radiance from water vapor and other gases in the atmosphere. Uncertainty in the radiance measurement, the water vapor burden, and the representation of the water vapor continuum in radiative transfer models all contribute to the uncertainty in microphysical retrievals that use IR radiance measurements. Retrieval algorithms that use radar and lidar measurements also have difficulty retrieving cloud properties in low optical depth clouds ($\tau<0.1$). Thin clouds often go undetected by cloud radar because these clouds are often composed of small ice crystals that are much smaller than microwave wavelengths. Lidar can also have difficulty detecting thin clouds during daytime hours because visible wavelength lidar measurements can suffer from poor signal-to-noise ratio due to strong background sunlight.

Figure 1 demonstrates the difficulty in retrieving cloud properties in optically thin clouds. During the time period of 1700 to 1900 Universal Time Coordinates (UTC), a thin cloud is detected by both the radar and lidar. There is considerable scatter in the optical depth retrievals (Figure 1 g and h). The Raman lidar optical depth is considered to be the most accurate estimate and is used as the reference. The non-IR based algorithms (ZV, LR, EMP) all demonstrate scatter around the Raman values. In particular, the Donovan-LR optical depths are much larger than the other algorithms and the ZV and empirical optical depths are typically smaller than the Raman values during the 1700-1900 UTC time period. The Wang-LR algorithm follows the Raman values closely, but uses the Raman lidar extinction in its retrieval. In this case, several AERI based retrievals agree reasonably well with the Raman values and the LIRAD optical depths exhibit scatter both above and below the Raman values for very thin clouds. The Matrosov-ZIR algorithm does not report $\tau<0.1$ and the Mace-ZIR retrieval is larger than the Raman values, but only reports a few data points. The lack of data points for the ZIR algorithms demonstrates the difficulty of both radar and IR based algorithms when retrieving cloud properties in thin, tenuous clouds.

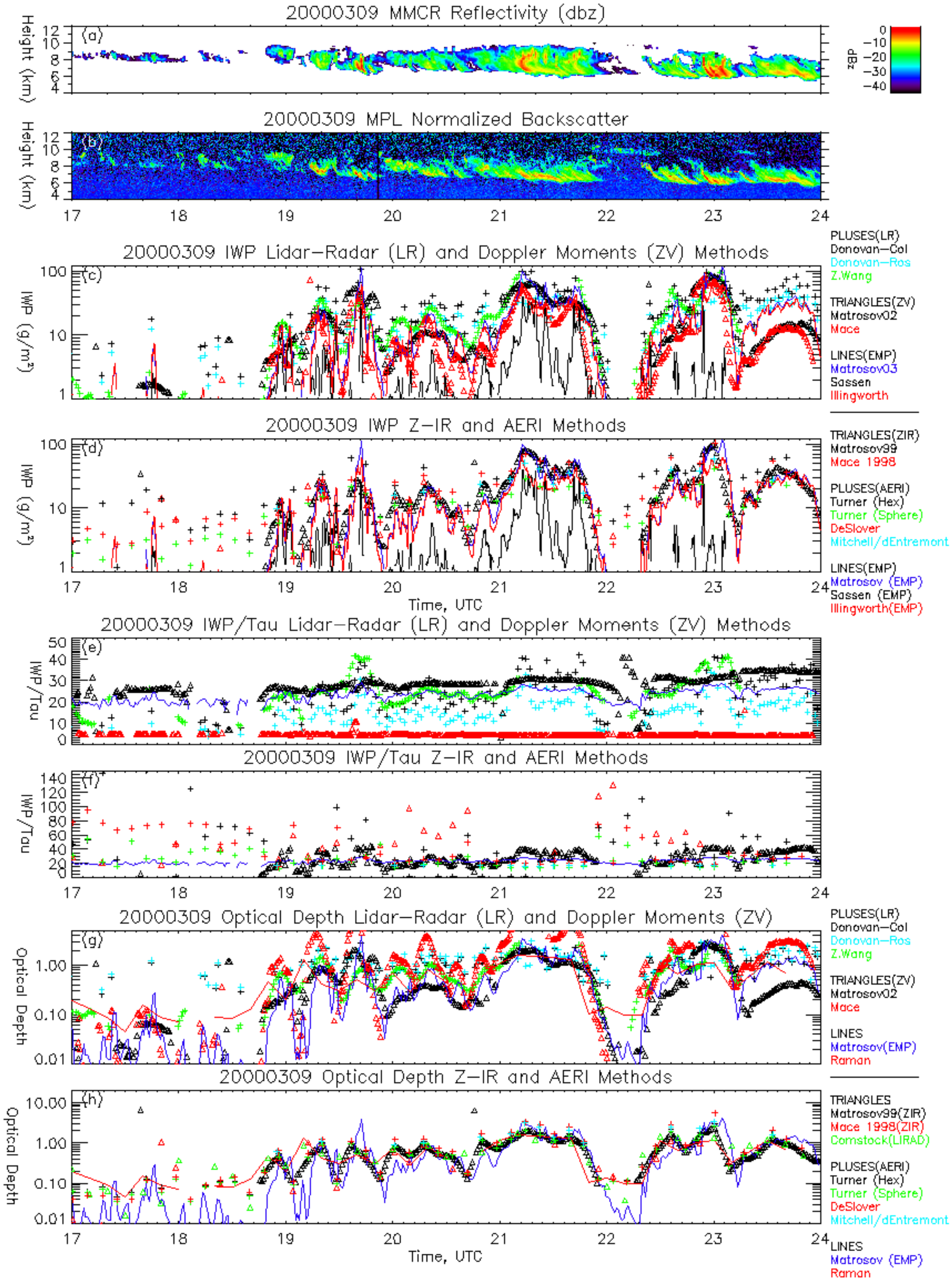

Figure 1. Algorithm intercomparison on 9 March 2000 during the March 2000 Cloud IOP. The panels display (a) MMCR (Millimeter wave Cloud Radar) reflectivity, (b) Micropulse Lidar (MPL), (c) and (d) IWP, (e) and (f) characteristic particle size, and (g) and (h) optical depth.

The cloud IWP and particle size both contribute to the cloud optical depth. Therefore, we expect to see similar trends in the scatter of the IWP and particle size that we see in the optical depth. In the IWP and particle size figures, we use the empirical results as the reference, although it is not necessarily the most accurate retrieval. For particle size, there is general agreement for the non-IR based algorithms, with the exception of Mace-ZV, which is considerably smaller than the other algorithms (Figure 1e). In ZV-type algorithms, the particle effective radius is the primary retrieved quantity and other variables (i.e., IWP and τ) are derived by combining the effective radius with the radar reflectivity measurements. The small particle sizes in Figure1e are a result of our definition of the characteristic particle size (the ratio IWP/τ). The Mace-ZV algorithm produced realistic effective radii (not shown) and IWP on this day; however since the optical depth produced by the algorithm is typically larger than the other algorithms (Figure1g and 2g), the ratio IWP/τ is smaller than the other algorithms (Figure1e). The Donovan-LR algorithm is also typically smaller than the empirical results for thin cloud particle size. While the empirical, ZV, and LR algorithms all have a characteristic size less than 30 in very thin clouds (Figure1e), the AERI based results are often much larger (Figure1f).

For very thin clouds, the IWP for all algorithms is generally below 10 g m-2 and demonstrates considerable scatter. Three empirical relationships are included in this comparison. The Liu and Illingworth (2000; LI-EMP hereafter) relationship is based on a combination of previously published empirical formulas relating radar reflectivity and IWC and is the current parameterization used in the micro_base VAP. For very thin clouds, the LI-EMP and Matrosov-EMP curves give similar results, but the LR, and AERI retrievals are typically higher than these empirical results.

Thin Clouds ($0.1<\tau<1.0$)

The thin cloud category is where most algorithms perform best. The IR-based algorithms detect significant cloud radiance and the lidar and radar based algorithms have little difficulty detecting clouds in this range. There are several time periods in both Figures 1 and 2 that clearly demonstrate the ability of these algorithms to retrieve cloud properties for thin clouds. For example, between 0000-0100 and 0430-0900 UTC in Figure2 the agreement in optical depth, IWP and particle size is quite good, particularly for the IR-based algorithms (Figure2d, f, and h). For optical depth, the ZV and EMP results are typically smaller than the Raman data, and the Donovan-LR results are slightly larger. The ZIR and Comstock-LIRAD algorithms both compare well with the Raman results. Several time periods in Figure2 again show where the agreement breaks down as the optical depth drops below 0.1 (0200-0430 and after 1400 UTC). Similar results are seen in Figure1 during periods with thin clouds.

For particle size, all algorithms are retrieving D less than ~40, with some scatter. In particular, the Mace-ZIR, Turner-Hex-AERI, and Matrosov-ZV are all slightly higher than the empirical results, while the Donavon-LR is typically lower for thin clouds. The Wang-LR, Turner-Sphere-AERI, DeSlover-AERI, and Matrosov-ZIR all track well with the empirical results.

The three empirical IWP retrievals agree relatively well in thin cloud cases. The result of Sassen-EMP is slightly lower than the other retrievals of IWP including the other empirical results. Both of the ZV algorithms agree with the empirical IWP results. The LR, Z-IR and AERI retrievals are generally higher than the empirical IWP values in thin clouds.

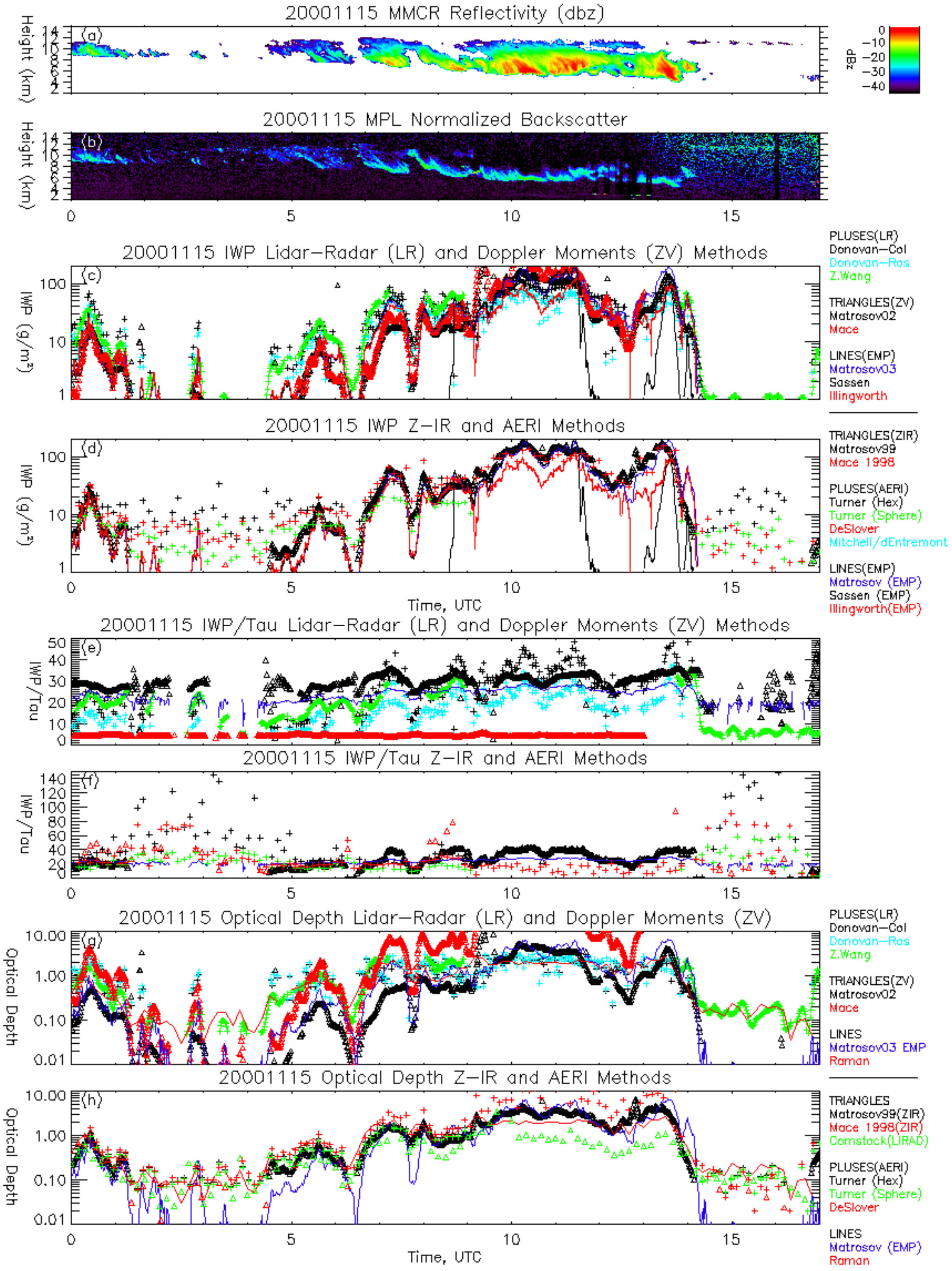

Figure 2. Algorithm intercomparison on 15 November 2000.. The panels display (a) MMCR (Millimeter wave Cloud Radar) reflectivity, (b) Micropulse Lidar (MPL), (c) and (d) IWP, (e) and (f) characteristic particle size, and (g) and (h) optical depth.

Thick Clouds (τ>1)

Thick ice clouds with τ>1 also pose a challenge for many of the retrieval algorithms. In particular, lidar signals become attenuation limited when the optical depth reaches 2 to 3. This limits the penetration depth through the cloud. Both cases in Figures 1 and 2 have regions when the lidar is attenuation limited, but it is particularly evident in Figure 2b between 0900 and 1330 UTC when the lidar cloud top height is only ~8 km. The radar is able to penetrate through thick clouds and detects cloud up to ~12 km (Figure2a). Retrieval algorithms that utilize IR radiance will also have some difficulty in thick clouds when the IR signal from the cloud becomes saturated. The radar only algorithms (ZV) should perform best in thick clouds.

Since the lidar is attenuation limited in thicker clouds, the Raman lidar optical depth will be lower than the true optical depth, but we will continue to use it as the reference. The Matrosov-ZV, DeSlover-AERI, and empirical algorithms produce the largest optical depths (0900-1330 UTC Figures 2g and 2h). The Donovan-LR algorithm will compute the microphysical properties only in sections where both the radar and lidar detect cloud. Therefore, it is not surprising that the optical depth and IWP is smaller than the radar ZV algorithms. The Comstock-LIRAD optical depth is much lower than the other retrievals in thick clouds and the Wang-LR and Turner-AERI algorithms do not report values when the cloud becomes too thick.

Particle size results for thick clouds are similar to the thin cases. The exceptions are the Matrosov-ZIR and DeSlover-AERI algorithms, which give smaller particle size than the empirical and Donovan-LR algorithms. The Donovan-LR algorithm provides results for two ice crystal shapes and is smaller than Matrosov-EMP for rosettes and larger than both Matrosov-EMP and Matrosov-ZV for hexagonal columns.

For IWP, we would expect the two ZV algorithms to produce similar results and the largest values because ZV retrievals can utilize the full cloud depth. However, the two ZV algorithms have fairly significant differences for the largest IWP (i.e., 50-100 g m-2 in Figure 2c between 1000 and 1100 UTC) and the trend is not consistent. For instance, the Mace-ZV algorithm IWP is smaller than the Matrosov-ZV algorithm in Figure1c but larger in Figure2c in the thickest portions of the cloud. Although these two algorithms are fundamentally the same, their results are sensitive to specified coefficients used in the retrievals. In particular, there is large uncertainty in isolating the fall velocity of ice crystals from the Doppler velocity measurement, which is critical to the ZV retrievals. The Sassen-EMP IWP values are typically lower than the other retrievals in thick clouds, particularly in Figure1c and 1d. Although, the Matrosov-ZIR and DeSlover-AERI results track the Sassen-EMP and Matrosov-EMP curves well in Figure2d. LI-EMP is also lower in Figures 2c and 2d. The LI-EMP relationship, which is currently used in the micro_base VAP, deviates from other retrievals primarily in the thickest clouds. In the thick cloud region in Figure1, the optical depth approaches only 2-3, so the Wang-LR is able to retrieve an IWP that agrees well with other algorithms (Figure1c).

Summary and Future Work

In this intercomparison of 13 different retrieval algorithms for upper tropospheric ice clouds, we examined several different types of algorithms that utilize different combinations of remote sensors. We grouped the results according to algorithms that use similar assumptions, and found that three optical depth regions best identify the strengths and weaknesses of each class of algorithm. The good news in the findings is that most algorithms converge for thin clouds with optical depth between 0.1 and 1.0, which constitutes the majority of midlatitude cirrus cloud observations (Sassen and Comstock 2001). However, there are significant discrepancies in very thin clouds ($\tau<0.1$). These clouds will not have a significant impact on the radiation budget in midlatitude regions, but can produce significant warming in the cold upper troposphere typically found in the tropics. In general, the IWP comparisons show good agreement and typically vary by a factor of 2 to 5. The ZV algorithms are the only techniques that can consistently retrieve properties from thick clouds and has the added benefit of providing results when multiple cloud layers exist and low opaque clouds block high cirrus clouds. However, there is still some work that needs to be done to supply the correct coefficients for ice crystal fall speed estimates. Further in situ measurements will help to reduce the uncertainty in these coefficients.

In this preliminary study, we did not attempt to identify the “best” algorithm. This is the subject of future work that will involve both flux and radiance closure studies for various cloud thicknesses. This will be difficult for ice clouds because most algorithms are sensitive to assumptions of particle habit, which will impact radiative transfer simulations. Radiative flux closure is also problematic due to 3D effects, which can increase uncertainty caused by the inherent inhomogeneity of cirrus clouds. Another option is to perform radiance closure using a narrow field-of-view instrument to minimize the 3D effects. We will also compare with any in situ data that coincides with our chosen cases. Eventually we will need to examine a larger statistical sample for the algorithms that are identified as having the most potential. One approach to evaluating how well an algorithm performs is to compare results with a simple algorithm, such as an empirical relationship. By using a large sample size, if the more complex algorithm performs better than the empirical retrieval, then it likely has some skill in retrieving cloud microphysical properties.

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